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A multi-hazard risk assessment methodology, stress test framework and decision support tool for transport infrastructure networks

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Abstract

Natural hazards can cause serious disruption to societies and their transport infrastructure networks. The impact of extreme hazard events is largely dependent on the resilience of societies and their networks. The INFRARISK project is developing a reliable stress test framework for critical European transport infrastructure to analyse the response of networks to extreme hazard events. The project considers the spatio-temporal processes associated with multi-hazard and cascading extreme events (e.g. earthquakes, floods, landslides) and their impacts on road and rail transport infrastructure networks. As part of the project, an operational framework is being developed using an online INFRARISK Decision Support Tool (IDST) to advance decision making approaches, leading to better protection of existing transport infrastructure. The framework will enable the next generation of European infrastructure managers to analyse the risk to critical road and rail infrastructure networks due to extreme natural hazard events. To demonstrate the overarching risk assessment methodology developed in the project, the methodology is demonstrated for two case studies, which comprise portions of the European TEN-T network; a road network in the region of Bologna, Italy and a rail network extending from Rijeka to Zagreb in Croatia. This paper provides an overview of the INFRARISK multi-hazard risk assessment methodology and a brief introduction to the case studies, as the project is currently ongoing. INFRARISK is funded by the European Commission's FP7 programme, Grant Agreement No. 603960. Further information can be found at www.infrarisk-fp7.eu.

Keywords: Transport infrastructure; Natural hazards; Climate change; Stress testing; Risk assessment.

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1. Introduction

Rare, extreme natural hazard events can have a devastating impact on societies and their infrastructure networks. In recent decades, the complex interdependencies of European infrastructure networks have been highlighted through cascading and escalating failures during extreme hazard events. For example, the floods experienced in central Europe in August 2002 resulted in the deaths of approximately 150 people and an estimated €150 billion worth of damage (Toothill, 2002). Germany and the Czech Republic were worst affected, experiencing damage to approximately 250 roads and 256 bridges, as well as electricity failures, disruptions to telecommunication links, disruptions to gas services, and contamination of water. Furthermore, the 2009 L'Aquila earthquake in Italy resulted in the deaths of over 300 people, over 10,000 damaged buildings, several damaged bridges, as well as earthquake-triggered landslides (Global Risk Miyamoto, 2009). To ensure the preparedness and the resilience of societies and their infrastructure networks to such extreme events, effective risk assessment and mitigation methodologies are required.

The INFRARISK project (*Novel Indicators for Identifying Critical Infrastructure at Risk from Natural Hazards*) is developing a multi-hazard risk assessment methodology to perform stress testing for European transport infrastructure networks due to low probability, extreme events. The stress test framework will enable infrastructure owners and managers to assess the risk to European road and rail networks, along with their structural components, to extreme hazard events. As part of the project, an online INFRARISK Decision Support Tool (IDST) is being developed that will provide the next generation of infrastructure owners and managers with the necessary tools to manage their transport networks.

The INFRARISK project is focused upon nodal 'land-links', e.g. roads, highways and railroads, and the associated structural components (e.g. bridges, tunnels, road and rail segments). The hazards considered include earthquakes and floods, as well as the associated triggering effects (i.e. earthquake-triggered landslides and rainfall-triggered landslides). The project considers the complex interdependencies of multi-hazards and their cascading effects, and their impacts on transport infrastructure networks. The spatial and temporal vulnerabilities of transport networks to extreme natural hazard events are incorporated into the methodology.

The INFRARISK project is funded by the European Commission's FP7 programme, Grant Agreement No. 603960. It commenced in September 2013 and is three years in duration. The consortium consists of a multi-disciplinary team that gathers 11 partners from 7 European countries: Roughan and O'Donovan Ltd., the Swiss Federal Institute of Technology in Zurich, Dragados SA, Gavin and Doherty Geosolutions Ltd., Probabilistic Solutions Consult and Training BV, the Spanish National Research Council, University College London, PSJ, Stiftelsen SINTEF, Ritchey Consulting AB, and the University of Southampton. It is led by Roughan and O'Donovan Ltd., one of Ireland's largest civil and structural engineering consultancies. Overall, the consortium comprises three research institutes/organisations, two higher education institutes, one large industry and 5 small-to-medium enterprises.

2. Research Focus

The focus of the INFRARISK project is the on the development of a stress test framework to assess the risk to critical European road and rail networks due to rare, extreme natural hazard events. This will aid decision making regarding the protection of existing transport infrastructure networks and the development of robust infrastructure networks for the future. In the framework of the INFRARISK project, the TEN-T road and rail core networks

(Figure 1) and their structural elements (e.g. bridges, tunnels, road and rail segments) are considered to be critical infrastructure in the context of the European transport network.

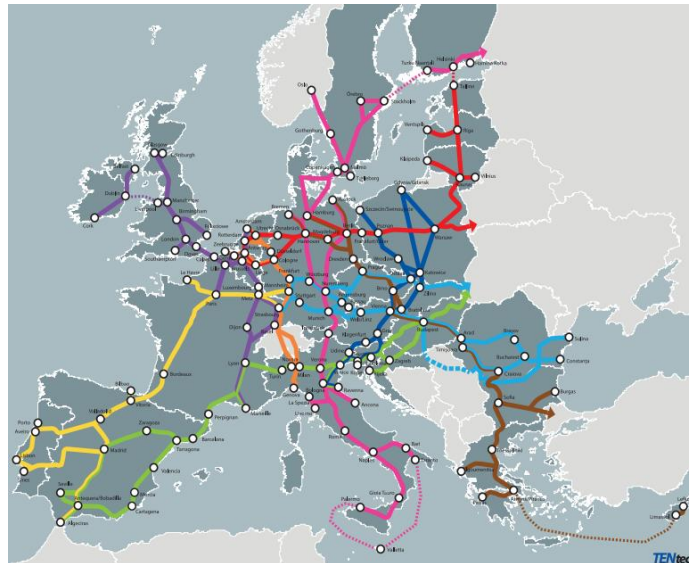


Fig. 1. European TEN-T Network

2.1. Hazards

The extreme hazards considered in the INFRARISK project are earthquakes, floods and landslides. The interactions and cascading effects associated with these hazards are illustrated in Figure 2.

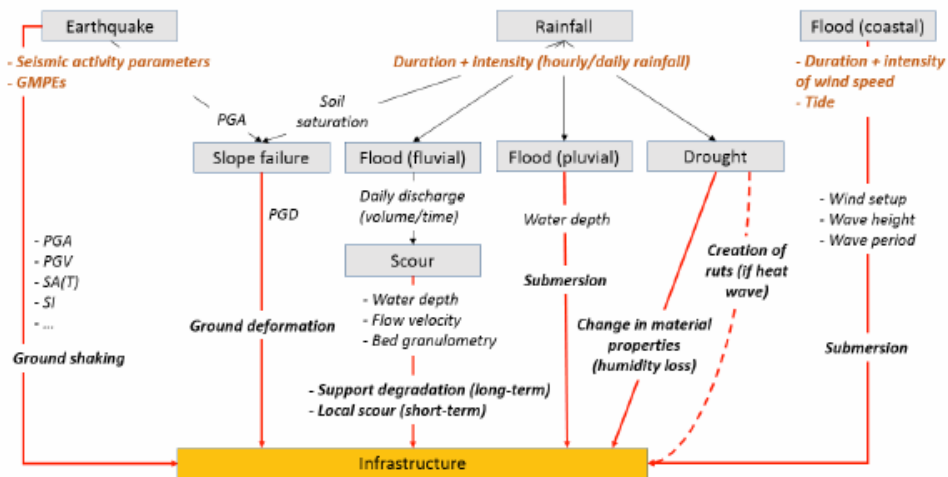


Fig. 2. Various hazards considered within INFRARISK framework

Although extreme hazard events are not frequent in many parts of Europe, their occurrence can have devastating consequences on transport infrastructure networks, consisting of physical damage to the network (i.e. direct consequences) and functional

disruptions at local and/or regional level, resulting in significant societal and economic losses (i.e. indirect consequences). Within the INFRARISK risk assessment methodology, initially each hazard is analysed individually to quantify the hazard intensity level at a given site of interest for a given source or triggering event (D'Ayala & Gehl, 2014).

3. Multi-Hazard Risk Assessment Methodology

The occurrence of earthquake, flood and landslide hazards, the response of the infrastructure network's structural components (i.e. bridges, tunnels, road and rail segments) and the response of the transport activities to a network disruption vary both spatially and temporally. The proposed INFRARISK multi-hazard risk assessment methodology explicitly considers the spatial and temporal correlation between the extreme natural hazard events and the functional interdependencies of the network objects. The INFRARISK multi-hazard risk assessment methodology follows the generalised risk management process illustrated in Figure 3 (Adey, et al., 2014). The proposed methodology is developed specifically for road and rail infrastructure networks; however the methodology may be adopted for other network types.

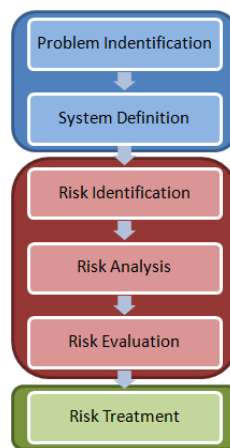


Fig. 3. Outline of INFRARISK risk assessment methodology

3.1. Problem Identification

The initial step involves identifying the problem, e.g. the infrastructure network to be examined, the associated hazards and the overall objective of the risk assessment.

3.2. System Definition

The next stage of assessment requires the system to be defined in terms of the system boundaries. To do so, specification of the spatial boundaries of the system is required, which consists of the geographical boundaries of the network, hazard events, and where the consequences may occur. In addition, it is necessary to define the temporal boundaries of the system. This involves defining the time period over which the risk is to be assessed, the number and size of intervals into which this period should be divided, and whether the system representation is static or dynamic. The system elements must also be defined. These may include the following: source events (e.g. tectonic plate movement, rainfall); hazard events (e.g. earthquakes, floods); infrastructure events (e.g. yielding of a bridge reinforcement bar, a bridge collapse); network events (e.g. closure of a freight corridor due to a tunnel collapse); societal events (e.g. 10% of goods are not delivered due to the closure of a freight corridor). Finally, it is necessary

to define the relationships between system elements (e.g. determining the amount of water coming into contact with a bridge during a flood).

3.3. Risk Identification

Once the problem and system elements have been defined, it is necessary to identify the associated risks. This involves the development of a set of scenarios to represent all combinations of the system elements.

3.4. Risk Analysis

To analyse the risk, the next step involves estimating the probability of occurrence of the scenarios and determining the associated consequences for each scenario. To do so, either a qualitative or a quantitative approach may be adopted, whereby the quantitative approach provides an accurate estimate of the probabilities of occurrence using a statistical analysis or probabilistic modelling (e.g. event trees, fault trees, Bayesian networks, Monte Carlo simulation).

3.5. Risk Evaluation

The risk associated with the network being analysed must then be evaluated in terms of the perception of stakeholders and decision makers.

3.6. Risk Treatment

Finally, where the risk levels are unacceptable, the risks must be treated by implementing appropriate interventions.

4. Stress Test Framework

Stress testing may be defined as the process of determining the ability of a network to maintain a certain level of effectiveness under unfavourable conditions. For transport infrastructure networks specifically, stress testing may be employed to determine the resilience of the network to extreme hazard events. The INFRARISK project is performing stress testing for transport infrastructure networks according to advanced simulation models. The stress tests involve evaluating the results of the multi-hazard risk assessment methodology according to specified criteria (Avdeeva & van Gelder, 2014). Within the INFRARISK stress test framework, there are three possible outcomes if the network fails the stress test: 1) a more detailed analysis is to be conducted for part of the network and no further stress tests are required, 2) a more detailed analysis is to be conducted for part of the system and further stress tests are required, 3) interventions may be specified to improve the infrastructure network.

5. INFRARISK Decision Support Tool

An online tool, known as the INFRARISK Decision Support Tool (IDST), is being developed as part of the project (Meacham & Sabeur, 2014) (Melas & Sabeur, 2015). This will integrate the overarching stress test framework, the risk assessment methodology and the various workflow processes involved. The IDST will consist of a user-friendly Graphical User Interface. Users of the IDST, such as infrastructure owners and managers, can apply the INFRARISK stress test framework to any transport network of interest provided that the relevant data is uploaded. Figure 4 illustrates the welcome page of the IDST v1.0. Additionally, the IDST will provide access to generated databases and results for two European case studies that are being examined as part of the INFRARISK project, as described in the following section.

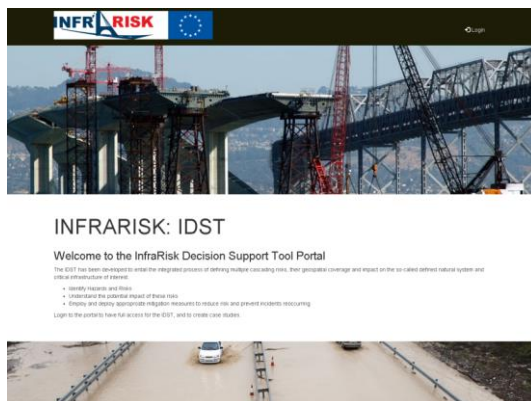


Fig. 4. INFRARISK Decision Support Tool (IDST) v1.0 welcome page (Melas & Sabeur, 2015)

6. INFRARISK Case Studies

To demonstrate the systematic application of the risk assessment methodology and stress test framework being developed in the INFRARISK project, two case studies are being examined as part of the project (Ni Choine & Martinovic, 2014). The first case study consists of a road network in Northern Italy in the vicinity of the city of Bologna (Figure 5a), for which earthquake and earthquake-triggered landslide hazards are considered. The second case study comprises a planned rail network in Croatia connecting the port of Rijeka to the city of Zagreb (Figure 5b) that is currently at design stage, for which floods and rainfall-triggered landslides hazards are considered. Both networks form part of the European TEN-T core network. An introduction to the application of the INFRARISK multi-hazard risk assessment methodology to the selected Italian road network is provided herein.

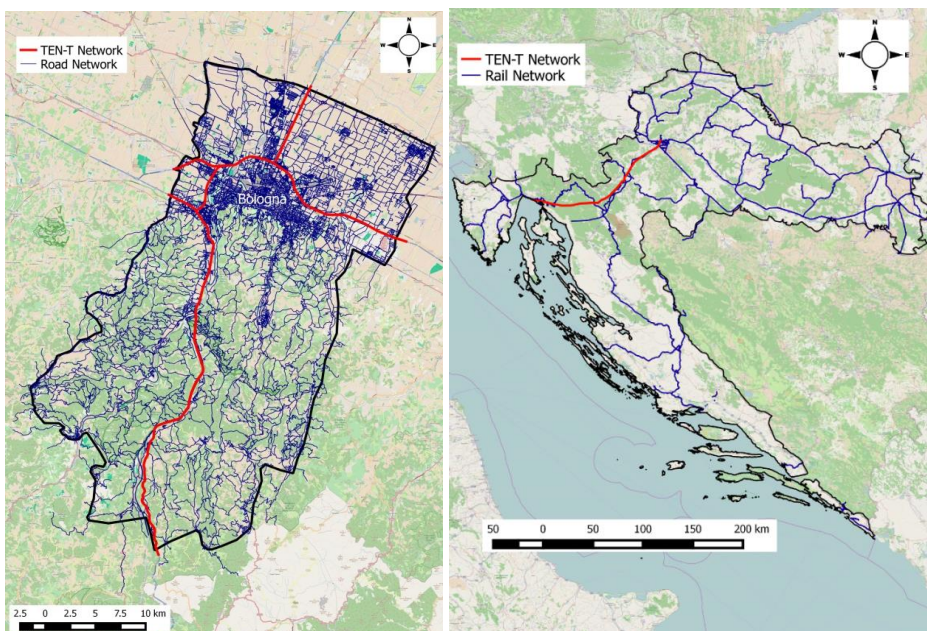


Fig. 5. INFRARISK case studies (a) Italian road network (b) Croatian rail network

6.1. INFRARISK Case Study: Italian Road Network

The area considered for the Italian road network in the region of Bologna in Northern Italy is approximately 990km² and the hazards considered for this region comprise earthquake and earthquake-triggered landslides. A geographic representation of the road network for this region was obtained from Open Street Map data (<http://download.geofabrik.de/europe/italy.html>) and details of the structural elements (i.e. bridges, tunnels and road segments) for this road network were subsequently obtained (Figure 6a). Overall, 340 bridges and 30 tunnels were identified and structural attributes (Hancilar & Taucer, 2013) were subsequently gathered according to a visual survey using Google Earth. In addition, roadways were classified as either major or urban. The susceptibility of the region to earthquakes was analysed according to a probabilistic seismic hazard analysis and the susceptibility of the region to earthquake-triggered landslides was analysed according to the calculation of landslide yield acceleration values (k_y) for the study area (Figure 6b) using a sliding block displacement approach (D'Ayala & Gehl, 2014).

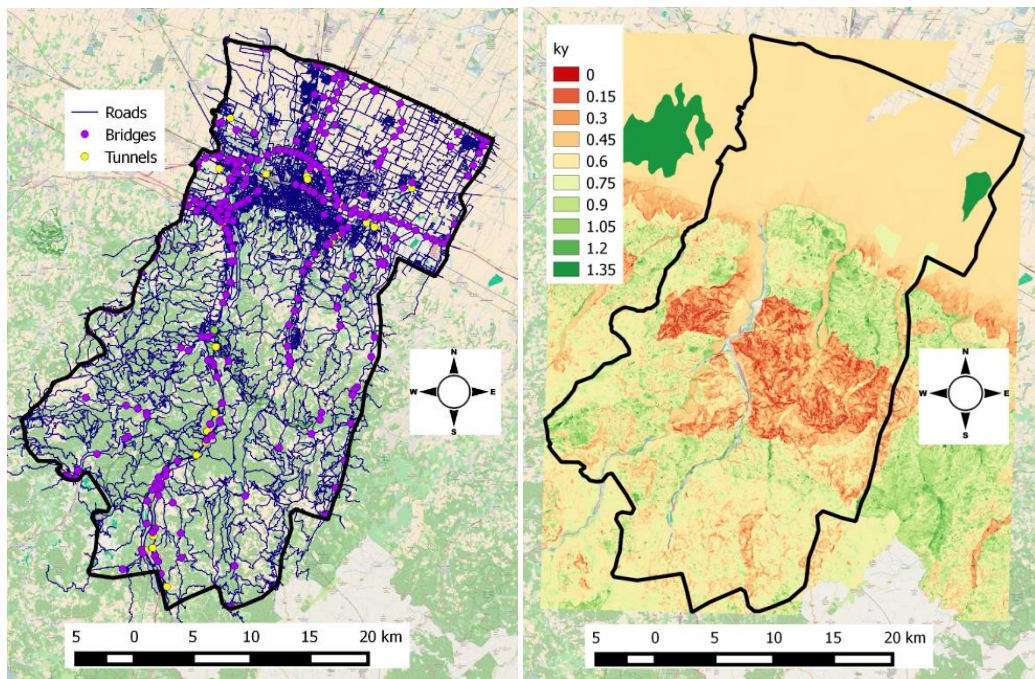


Fig. 6. Italian road network case study (a) location of bridges and tunnels (b) landslide yield acceleration (k_y) values

To determine the vulnerability of the road network to earthquakes and earthquake-triggered landslides, fragility curves were subsequently assigned to the structural elements (i.e. bridges, tunnels and road segments) to indicate the probability of exceeding specific damage states according to the ground motion intensity level (D'Ayala & Gehl, 2015). Example fragility curves for a road segment due to an earthquake-triggered landslide are illustrated in Figure 7 for three damage states (slight, moderate and extensive/complete).

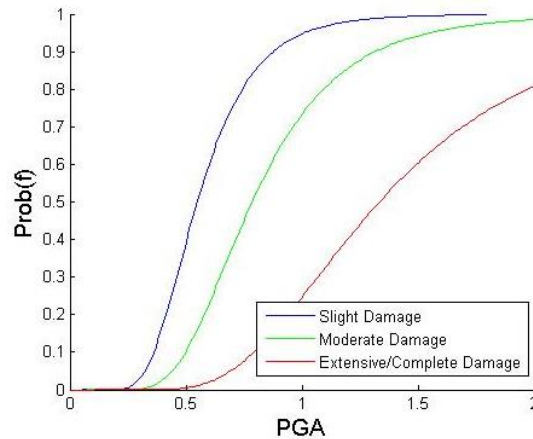


Fig. 7. Example fragility curves for an 'urban' roadway segment due to earthquake-triggered landslide hazard ($k_y = 0.2$).

To determine the risk to the road network due to earthquakes and earthquake-triggered landslides, damage sampling was subsequently conducted, enabling the associated direct and indirect consequences to be estimated. In the framework of the INFRARISK project, 'direct' consequences refer to the cost of physically restoring the network to the level of service that existed prior to the natural hazard event and, therefore, these losses are considered to be directly attributable to the infrastructure manager. 'Indirect' consequences refer to the costs associated with any further network or societal costs encountered due to the hazard event (e.g. lost working time due to additional travel time due to network disruptions).

7. Discussion and Conclusions

The aim of the INFRARISK project is to develop a stress test methodology to assess the risk to critical infrastructure networks due to extreme hazard events. The multi-hazard risk assessment methodology requires the context to be initially established through the identification of the problem and the definition of the system. A risk assessment is subsequently performed according to the identification, analysis and evaluation of the risks. This methodology fits within the encompassing INFRARISK stress test framework to determine the resilience of the overall network to low probability, extreme natural hazard events. This framework, as presented using on online IDST will provide transport infrastructure owners and managers with a decision making tool to manage the risks associated with extreme natural hazard events and to improve the resilience of transport infrastructure networks. An overview of the INFRARISK project has been outlined in this paper, along with an introduction to one of the case studies being conducted as part of the project.

8. Acknowledgements

INFRARISK is funded by the European Commission's FP7 programme, Grant Agreement No. 603960. Further information can be found at www.infrarisk-fp7.eu. The authors gratefully acknowledge the contributions of the other INFRARISK consortium partners: the Swiss Federal Institute of Technology in Zurich, Dragados SA, Gavin and Doherty Geosolutions Ltd., Probabilistic Solutions Consult and Training BV, the Spanish National Research Council, University College London, PSJ, Stiftelsen SINTEF, Ritchey Consulting AB, and the University of Southampton.

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